CHANGING WHAT'S POSSIBLE

Extremely Durable Concrete using Methane Decarbonization Nanofiber Co-products with Hydrogen (EERE - Pipeline H_2)

Modular Processing of Flare Gas for Carbon Nanoproducts (NETL - Flare Gas)

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Mija H. Hubler, co-PI, University of Colorado – Boulder (CU)
Team Members: Forge Nano (FN), National Ready Mixed Concrete Association (NRMCA)

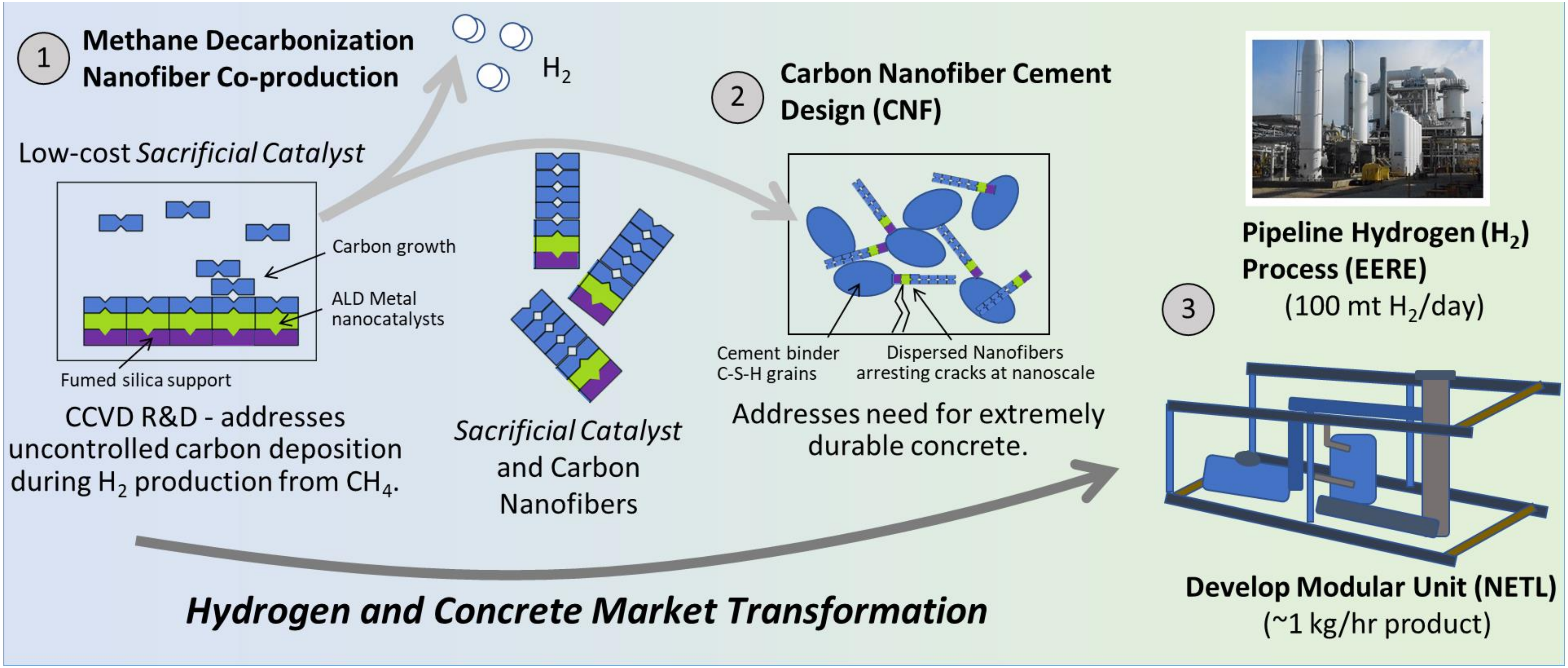
Project Vision

We are producing H_2 and a beneficial carbon nanofiber concrete additive from natural gas by chemical vapor deposition using a low-cost sacrificial and compatible catalyst support

Total Project Cost (mo)

EERE:	$1.25 M (36)
NETL:	$3.75 M (41)

The Concept and the Project Objectives



The Team

Alan Weimer (Chemical Engineering) PI

- **Kent Warren** Postdoctoral Fellow
- **Jessica Hauck** PhD Student
- **Robert Anderson** Principal Engineering Scientist

Mija Hubler (Civil Engineering) co-PI

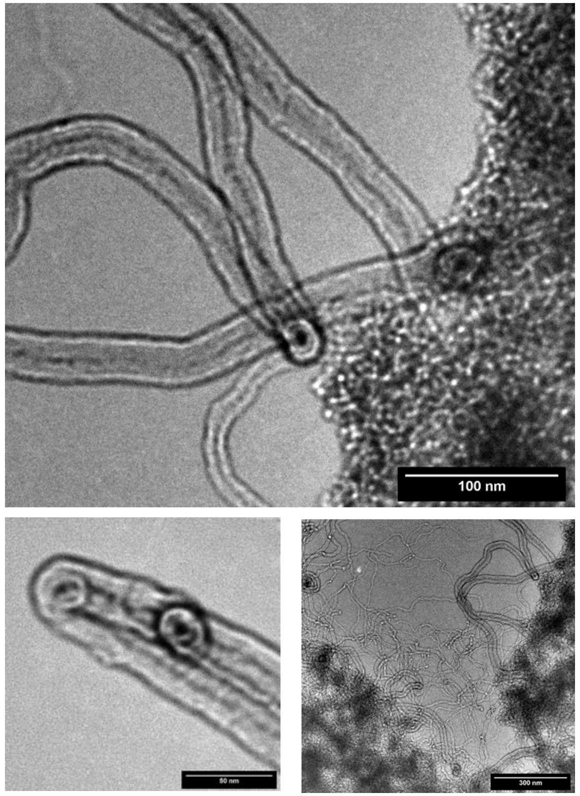
- **Linfei Li** Postdoctoral Fellow
- **Boning Wang** PhD Student

Collaborators

- Forge Nano
  - **Andrew Broerman** Principal Engineer
  - **Theodore Champ** Jr R&D Engineer
- National Ready Mixed Concrete Association (NRMCA)
  - **Colin Lobo** VP

EERE (Pipeline): In-situ Ambient Pressure ALD/CCVD Reactor

In-situ ALD/CCVD Reactor Constructed & Operated



Objective: *Investigate particle atomic layer deposition (ALD) catalysis to control carbon nanofiber (CNF) & "sacrificial" catalyst properties for the CO_2-free production of hydrogen.*

Pipeline Gas (EERE) Key Process Parameters	
Catalyst ALD fabrication	In-situ
Catalyst Support	Fumed Silica
Catalyst Metal	Monometallic (e.g, Fe, Ni, or Co)
Pressure Range	Ambient
Temperature Range	600 – 850°C
Scale-up	Pipeline centralized process
CNF application	High-performance concrete

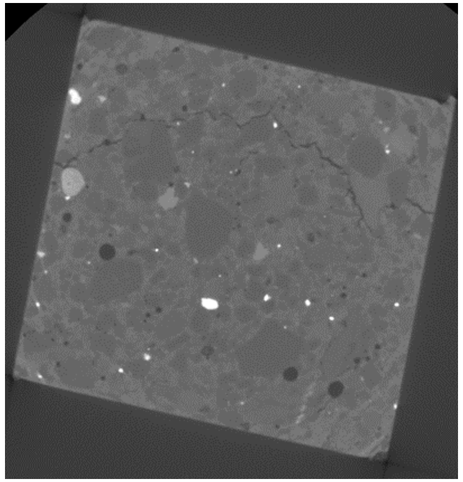
NETL (Flare Gas): Modular Skid Process Design and Construction

Flare Gas (NETL) Key Process Parameters	
Catalyst ALD fabrication	Ex-situ
Catalyst Support	Silica fume
Catalyst Metal	Bimetallic (e.g, Fe/Co, Ni/Co, Fe/Ni etc…)
Pressure Range	400 – 500 psig
Temperature Range	600 – 850°C
Scale-up	Modular process (1kg/hr)
Carbon Nanoproduct Application	Ultra high-performance concrete

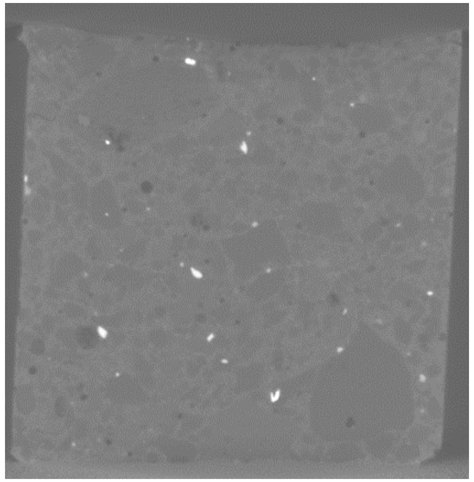
EERE: XRM images and test results for HPC

Optimized HPC mix design (kg/m^3)

	w/b	Cement	Water	Sand	SF	HRWR	Coarse aggregate	HPC requirements
Preliminary	0.29	487	155	676	47	11.22	1068	Meets strength
Optimized	0.29	487	155	676	47	11.22	1015	Meets strength & slump



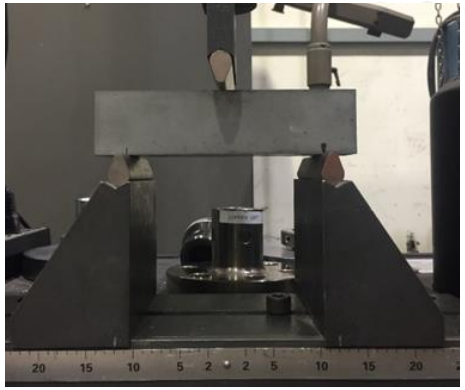
Samples without CNFs



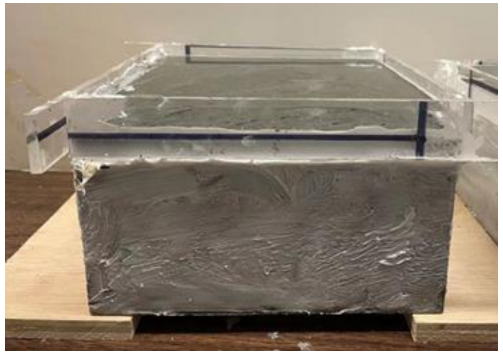
Samples with CNFs

For 1 cm mortar cube, after moist curing for 7 days under room temperature and oven drying for 7 days at 85°C, <u>XRM imaging showed that samples without CNFs shows clear cracks with the average size ~30μm, while samples with CNFs shows no clear cracks</u>.

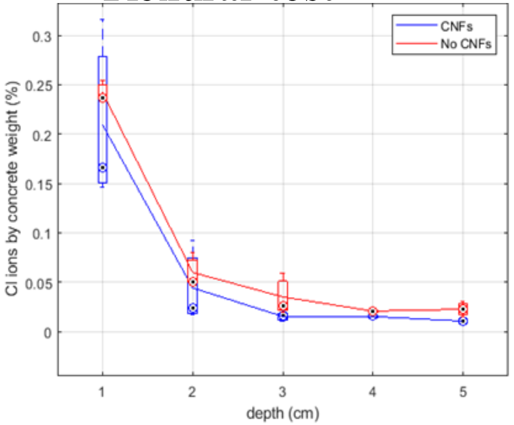
Compressive test



Flexural test



Ponding test

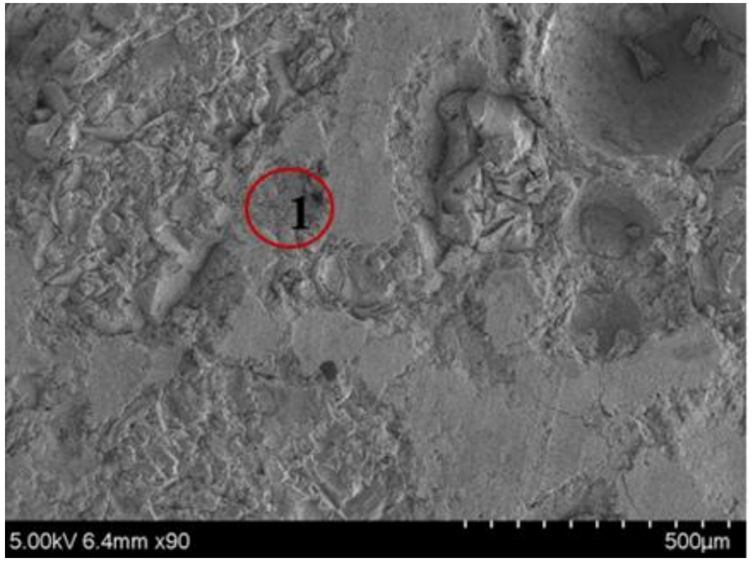


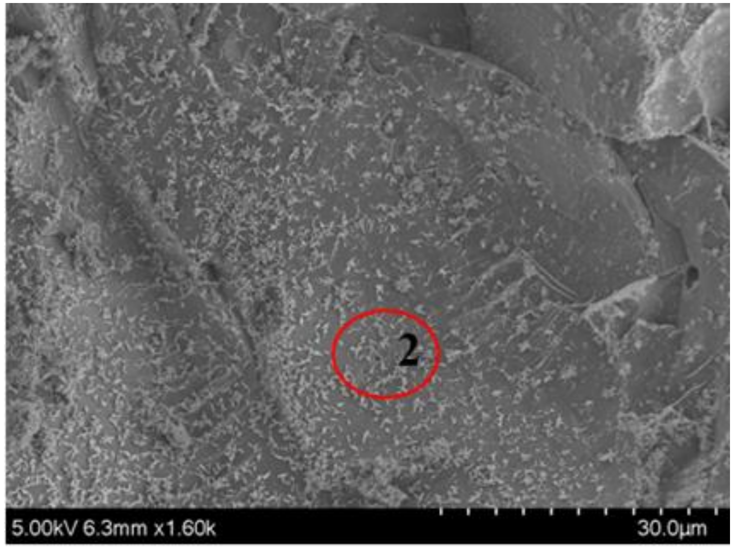
Ponding test results

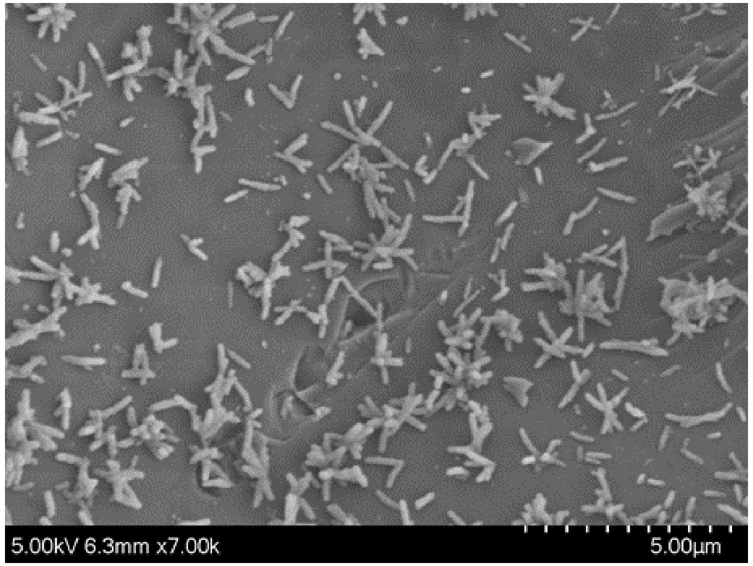
The addition of carbon resulted in a strength increase of 2% for 28-day compressive strength, 32% for 28-day flexural toughness and 29% for 3-month chloride resistance.

NETL: SEM images of dispersion in UHPC-CNFs

Well dispersed commercial CNFs in UHPC



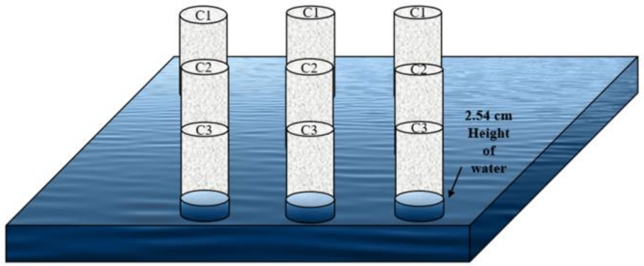


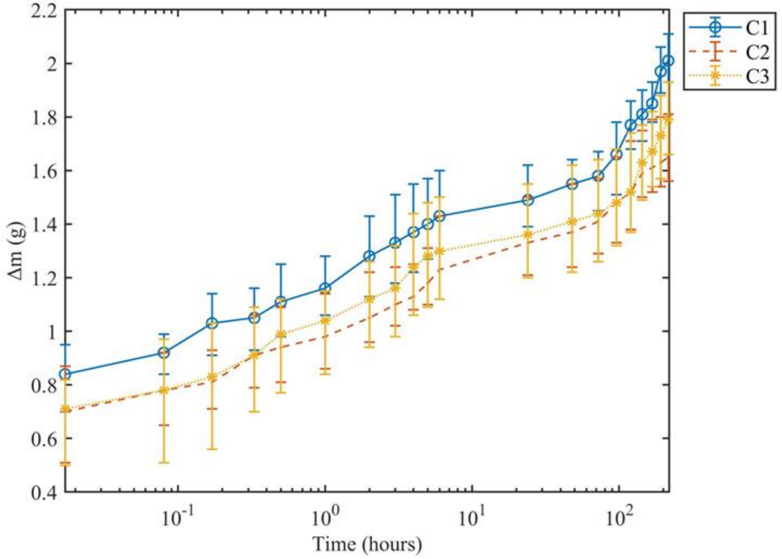


Commercial CNFs can be well dispersed in UHPC via selecting the most effective chemical surfactant and the optimized ultrasonic dispersion set up.

NETL: Permeability for UHPC with commercial CNFs

Wicking test

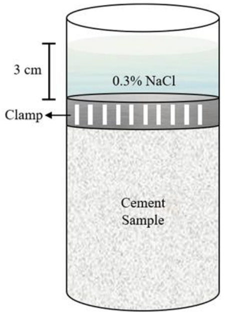


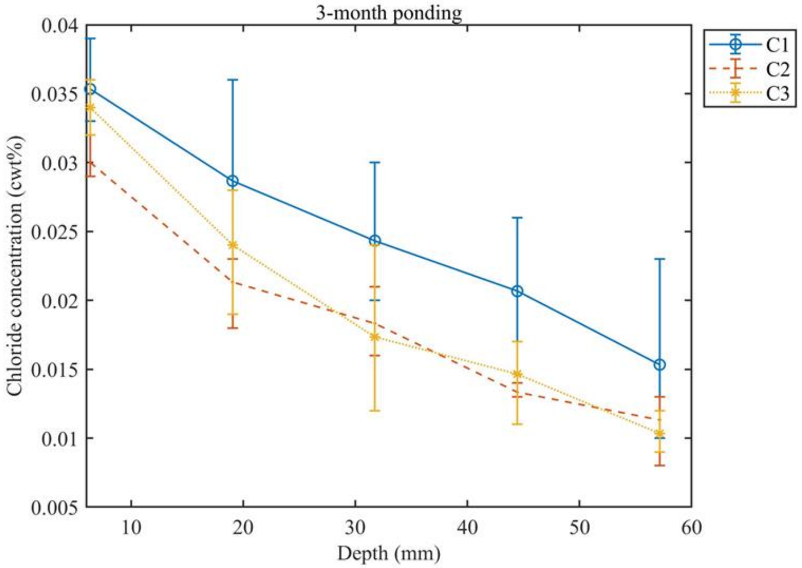


The magnitudes of the increment of the water & chloride resistance are up to 18% for 216-hour wicking test and 32% for 3-month ponding test, respectively.

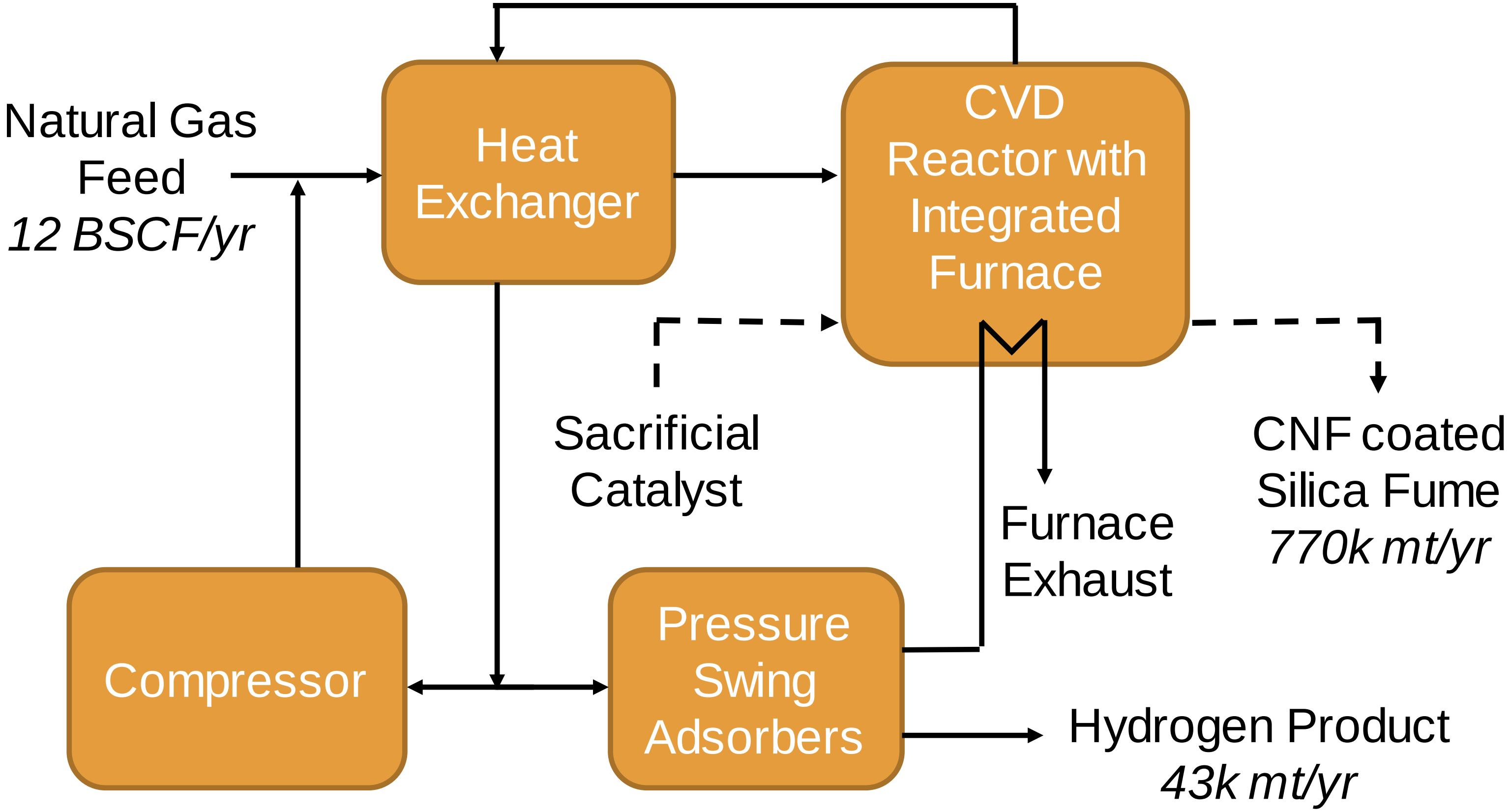
Specimen	Description
C1	Reference: UHPC only
C2	UHPC-CNFs; HRWR:CNFs=5:1 for dispersion
C3	UHPC-CNFs; HRWR:CNFs=10:1 for dispersion

Ponding test





EERE Results: Preliminary Technoeconomic Analysis



Experimental Data to Inform Future TEA

- Catalyst Loading [g Fe/g catalyst]
- Carbon Loading [g CNF/g Fe]
- Reactor Conversion

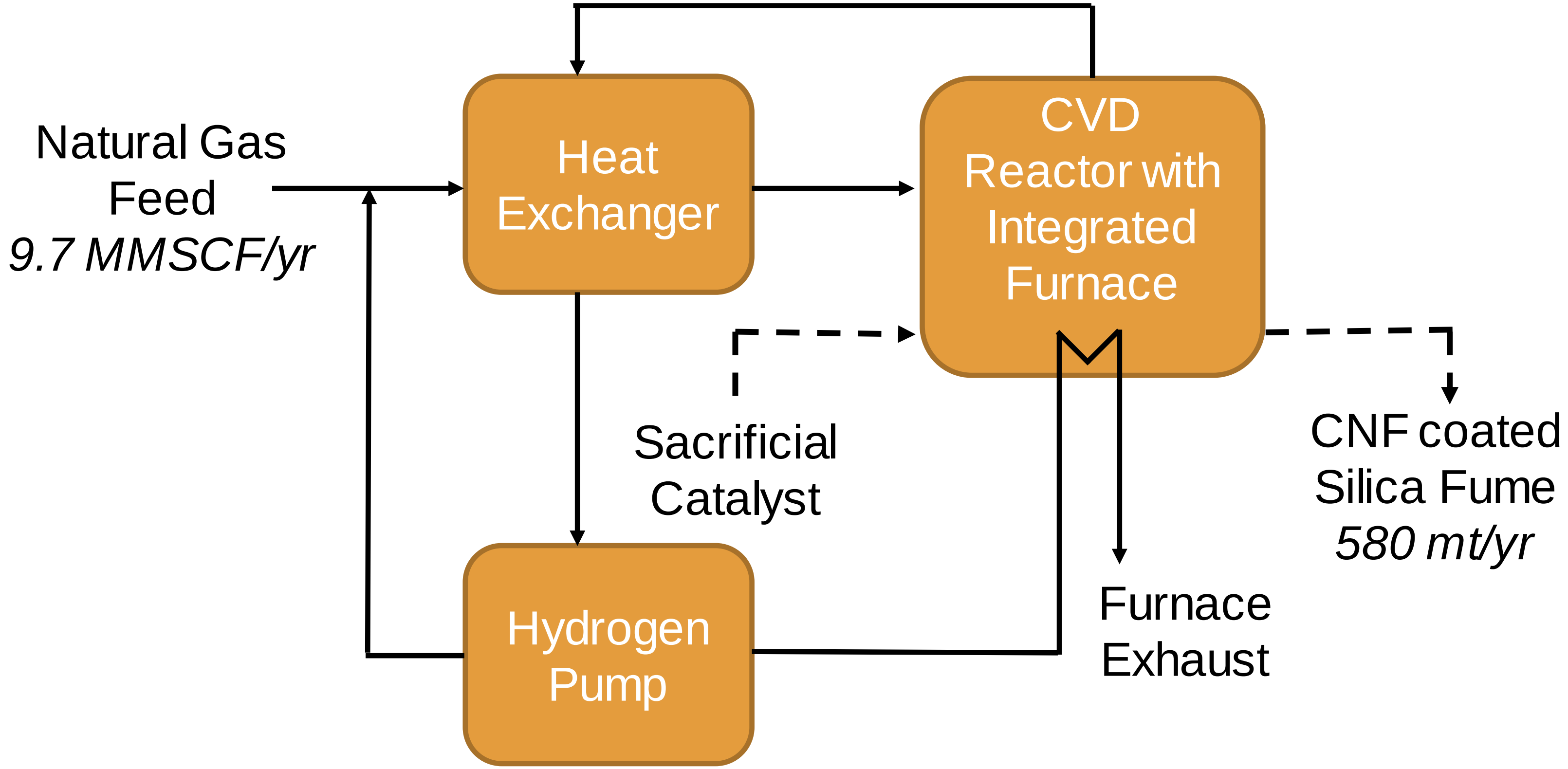
Parameters

Hydrogen price: $2/kg
NG cost: $3/KSCF
IRR: 10%
Lifetime: 15 years
Estimated TDC: $2B-4B
Cost of Capital: 8.5%

Results

CNF coated silica, price range:
$2 - $4 per kg
Pure CNF, price range:
$10 - $20 per kg
Pure CNF, current technology:
$300 per kg (bulk)

NETL Results: Preliminary Technoeconomic Analysis



Parameters

NG cost: Free
IRR: 10%
Lifetime: 15 years
Estimated TDC: $1M-2M
Cost of Capital: 8.5%

Results

CNF coated silica, price range:
$2 - $4 per kg
Pure CNF, price range:
$10 - $20 per kg
Pure CNF, current technology:
$300 per kg (bulk)

Experimental Data to Inform Future TEA

- Catalyst Loading [g Fe/g catalyst]
- Carbon Loading [g CNP/g Fe]
- Reactor Conversion

Challenges and Technical Partnerships

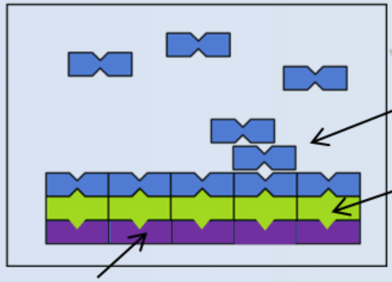
	CNF/CNP Synthesis	Cement Mixing	CVD Reactor Scale-up	Technology Implementation
Risk	Silica support may be completely covered by CNFs, limiting anchoring in cement mix.	The produced CNFs/CNPs may not be easily homogenized with cement.	There are unforeseen risks with process scale-up.	There are challenges with updating industry standards for technology implementation of CNF/CNP additives.
Risk Reduction	Metal nanoparticles are deposited *in-situ* using ALD resulting in highly dispersed metal nanocatalysts. Laboratory investigations will allow for fine control of catalyst properties to optimize CNF/CNP coverage.	Methods to ensure dispersion have been investigated using detergents and anti-foam agents.	Collaborating with Forge Nano for skid design, construction, and operation enables early identification of scale-up risks.	NRMCA has linked the research team with relevant contacts and the co-PI is engaged in committees writing standards for implementation.

T2M / Potential Impact

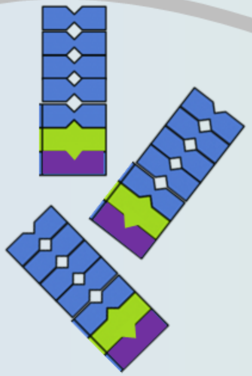
Chemical Engineering	*Civil Engineering*	*Potential Impact*

1 Methane Decarbonization Nanofiber Co-production

Low-cost *Sacrificial Catalyst*

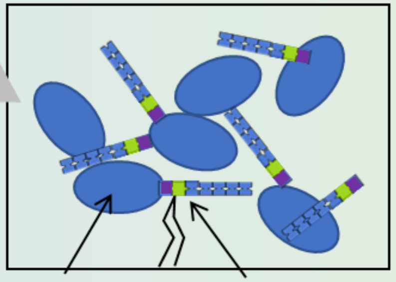


CCVD R&D - addresses uncontrolled carbon deposition during H_2 production from CH_4.



Sacrificial Catalyst and Carbon Nanofibers

2 Carbon Nanofiber Cement Design (CNF)



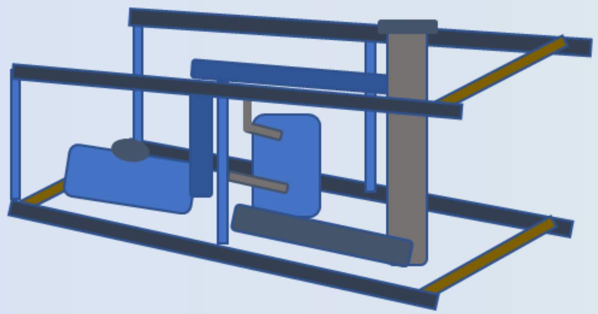
Addresses need for extremely durable concrete.

Hydrogen and Concrete Market Transformation

Potential Impact

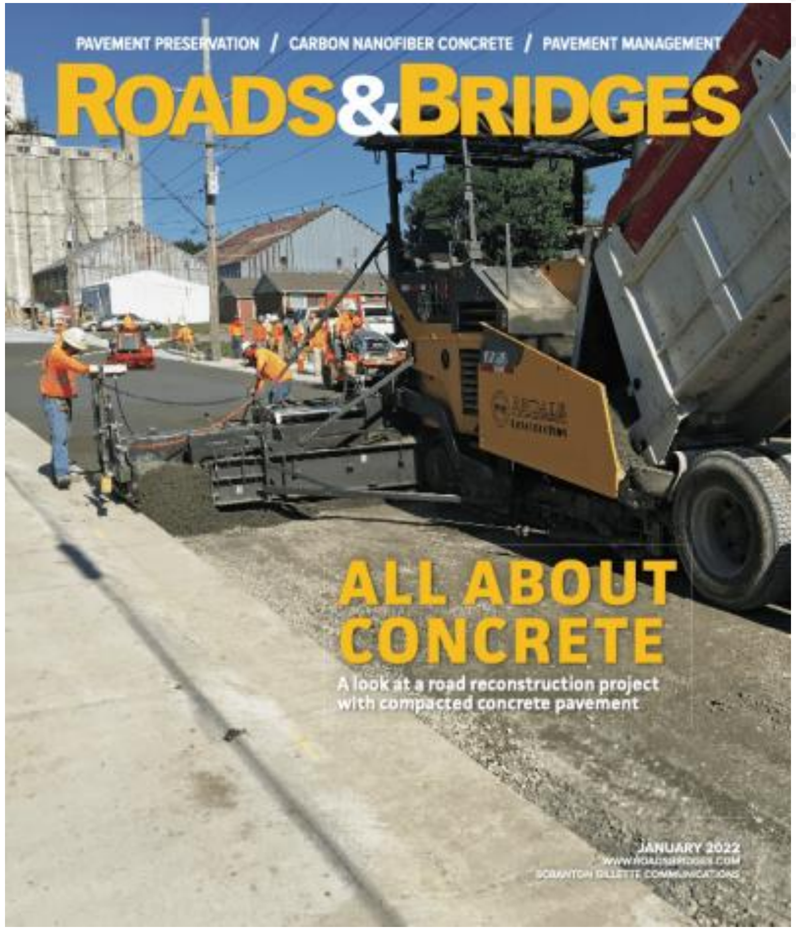
- Replace as much as 25% of H_2 produced in the US from steam methane reforming
- Carbon fiber product sequestered in concrete improves service life of concrete structures
- Process scales up to address both pipeline and flare natural gas sources

T2M / Potential Impact

Chemical Engineering *Scale-up Progress*	*Civil Engineering* *Potential Levers*	*Potential Impact*
• Modular unit operation expected 9/2022 – process will reach TRL 5 • Modular unit findings to inform technoeconomic analysis  **Modular Unit (NETL)** (~1 kg/hr product)	• Establishing a specification for the carbon product that can be referenced for permitted use in concrete • Documenting the performance benefits for specific applications to designers that can permit the use of the product in concrete • Developing guidance on use of product for concrete producers to incorporate product	• Replace as much as 25% of H_2 produced in the US from steam methane reforming • Carbon fiber product sequestered in concrete improves service life of concrete structures • Process scales up to address both pipeline and flare natural gas sources

T2M / Potential Impact

Indiana DOT completes first all-precast bridge replacement using carbon nanofiber UHPC



Collaborations

Fund-Receiving Collaborator		Project Roles
	ForgeNano	Reactor/process design and technoeconomic analysis
	National Ready Mixed Concrete Association (NRMCA)	Concrete materials, mix design, and consulting

Acknowledgements

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

NATIONAL ENERGY TECHNOLOGY LABORATORY

What questions do you have?